Chapter 6

Snake-Salt River Basin hydrogeology and groundwater resources

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Wyoming's groundwater resources occur in both unconsolidated deposits and bedrock formations. In terms of frequency of use, the primary hydrogeologic unit in the Snake/Salt River Basin is the Quaternary Snake/Salt River alluvium (Sunrise Engineering and others, 2003) (**figs. 8-1** through **8-7** and **pls. 4** through **6**). Additionally, over thirty five bedrock aquifers, ranging in geologic age from Paleozoic to Quaternary (**pls**. **2, 4, 5,** and **6**), exhibit heterogeneous permeability and provide variable amounts of useable groundwater.

Generally, aquifers are defined as geological units that store and transport useable amounts of groundwater while less permeable, confining units impede groundwater flow (**section 5.1.1**). In practice, the distinction between aquifers and confining units is not so clear. A geologic unit that has been classified as confining at one location may act as an aquifer at another. Virtually all of the geologic units in the Snake/Salt River Basin, including confining units, are capable of yielding at least small quantities of groundwater. For example, the Phosphoria Formation is classified as both an aquifer and a confining unit in the Snake/Salt River Basin, and several springs discharge water from this formation at the surface (**pl. 3**). Permeability can vary widely within an individual geologic unit depending on its lithology and the geologic structure present. Carbonate aquifers, such as the Madison Limestone, commonly exhibit the highest yields in areas where secondary permeability (e.g., solution openings, bedding plane partings, and fractures) has developed. The great differences in permeability between and within geologic units account, in part, for the observed variation in the available quantity and the quality of a basin's groundwater resources.

One of the primary purposes of this study is to evaluate the groundwater resource of the Snake/Salt River Basin primarily through the following tasks (**chapter 1**):

- Estimate the quantity of water in the aquifers,
- Describe the aquifer recharge areas,
- Estimate aquifer recharge rates; and
- Estimate the "safe yield" potential for the aquifers.

Although an enormous quantity of groundwater is stored in the Snake/Salt River groundwater basin, the basin's complex geology (**chapter 4**) does not permit the use of the general assumptions regarding aquifer geometry, saturated thickness, and hydraulic properties. Hydrogeologists commonly employ these assumptions to calculate a plausible estimate of total and producible groundwater resources. The data required for a basin-wide, aquifer-specific assessment of groundwater resources is not available and is unlikely to ever be developed. Therefore, groundwater resources evaluated in this study rely on previous estimates (Hamerlinck and Arneson, 1998) of the percentage of precipitation in areas where aquifer units outcrop that will ultimately reach the subsurface as recharge (**figs**. **6-1** through **6-6**) and the formulation of a basin-wide water balance (**chapter 8**). The technical and conceptual issues concerning recharge are discussed in **section 5.1.3**.

Similarly, the extensive hydrogeologic data required to estimate the safe yield of groundwater for the entirety of the Snake/Salt River Basin does not exist. Furthermore, geoscience has evolved beyond the concept of safe yield since it was first introduced by Lee (1915), and many scientists and water managers have largely abandoned this principle in favor of concepts such as sustainable development. The recharge volumes estimated in this chapter provide a first step to evaluating sustained yields for the basin's hydrologic units. The historical development of the safe yield concept and its technical context is discussed in **section 5.1.4**.

6.1 Hydrostratigraphy and recharge to aquifer outcrop areas

To begin the process of evaluating recharge, specific aquifers and groups of aquifers to which the recharge calculations will be applied must be distinguished (**figs**. **6-1** through **6-6**). Several previous studies (**section 2.1**) have grouped the Snake/Salt River Basin's hydrogeologic units into various combinations of aquifers, aquifer systems, and confining units. The hydrostratigraphy developed for this study is based on previous regional assessments and is summarized in the hydrogeology map illustrated in **plate 2** in the hydrostratigraphic charts shown on **plates 4** through **6** and in **chapter 7**. The hydrostratigraphic charts in **plates 4, 5, 6** detail the hydrogeologic nomenclature used in previous studies, including the aquifer classification system from the Statewide Framework Water Plan (WWC Engineering and others, 2007). **Appendix A** describes the geologic units used to develop the surface hydrogeology shown on **plate 2**.

Section 5.2 discusses how the map units of Love and Christiansen (1985), previously compiled into a Geographic Information Systems (GIS) database by the U.S. Geological Survey (USGS) and Wyoming State Geological Survey (WSGS), were used to develop **plate 2**. Love and Christiansen (1985), however, were not able to distinguish all stratigraphic units present in the Snake/Salt River Basin due to the sheer size of the dataset and cartographic limitations. Therefore, some geologic units were not mapped individually but instead, are shown on **plate 2** as undifferentiated hydrogeologic units. To address this deficit, the outcrops of hydrogeologic units that were assigned as aquifers or aquifer groups in **plate 2** are aggregated by geologic age. These aggregated aquifers, or aquifer recharge zones, were generated as GIS shapefiles and used to calculate recharge volumes and rates:

- Quaternary aquifers (**fig. 6-1**)
- Tertiary aquifers (**fig. 6-2**)
- Mesozoic aquifers (**fig. 6-3**)
- Paleozoic aquifers (**fig. 6-4**)
- Precambrian aquifers (**fig. 6-5**)
- Volcanic aquifers (**fig. 6-6**)

6.2 Average annual recharge

Only a fraction of the groundwater stored in the Snake/Salt River Basin can be withdrawn for beneficial use because groundwater naturally discharges to streams, springs, lakes, and wetlands and is further lost through evapotranspiration. Under natural conditions, a state of dynamic equilibrium in which natural discharges to surface waters and evapotranspiration are counterbalanced by recharge exists. In effect, this balance means that higher rates of recharge result in higher levels of natural discharge over time. Withdrawals from wells and springs remove groundwater from aquifer storage and natural discharges. Thus, without careful management, flows in springs, streams, and wetlands, as well as aquifer storage, will be depleted to such a degree that water rights holders will not receive their full appropriation and riparian ecosystems will collapse. This risk has long been recognized by Wyoming's agricultural community, as well as water managers for municipalities and conservation districts, state water administrators, and legislators. The connection between surface water and groundwater resources has been incorporated into Wyoming's water law and also forms one of the core tenets in forming some of Wyoming's interstate water compacts, such as the Amended Bear River Compact of 1978 and 2001 Modified North Platte River Decree.

To evaluate recharge on a regional scale, this study combines estimated, average annual recharge data from the Spatial Data and Visualization Center (SDVC) (Hamerlinck and Arneson, 1998) and WSGS maps illustrating where pertinent hydrogeologic units outcrop in the Snake/Salt River Basin (**pl. 2**; **figs. 6-1** through **6-6**).

Average annual recharge constrained by best estimates of annual discharge (both natural and by pumping) and periodic water level monitoring provide valuable baseline data. These data assist in establishing benchmarks for sustained yield, namely the volume of water that can be artificially discharged without unacceptably depleting aquifer storage or natural discharges. While aquifer-specific recharge can be reasonably estimated, aquifer-specific discharges are difficult to constrain. Estimates of annual groundwater withdrawals and consumptive uses from the previous Snake/Salt River Basin water plans (Sunrise Engineering, 2003; WWDO, 2012) and the Statewide Framework Water Plan (WWC Engineering and others, 2007) are discussed in **chapter 8**.

Estimated, average annual, recharge (**fig. 5-2**) in the Wyoming portion of the Snake/Salt River

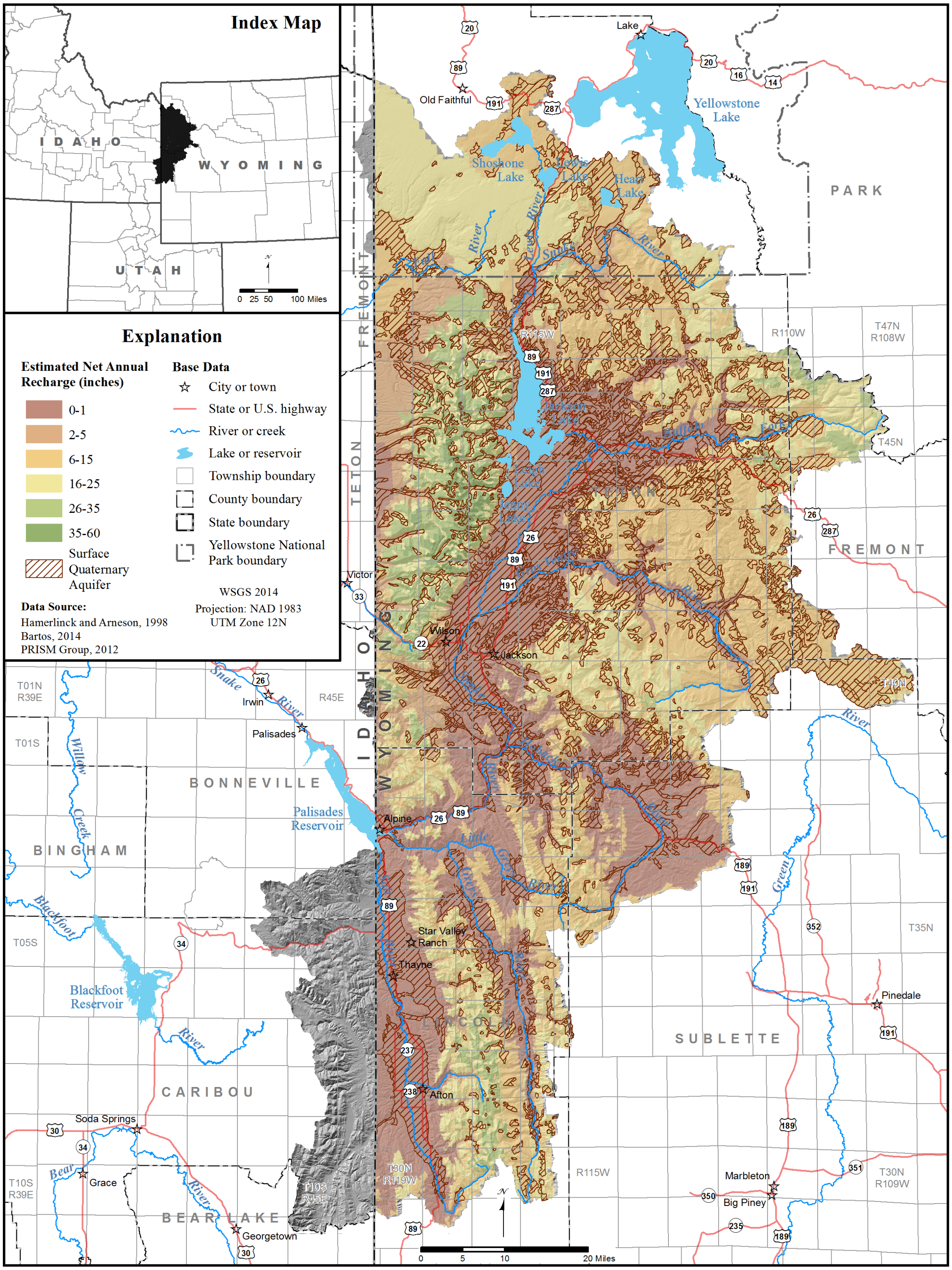

Figure 6-1. Estimated net annual aquifer recharge – surface Quaternary aquifer, Snake/Salt River Basin, Wyoming.

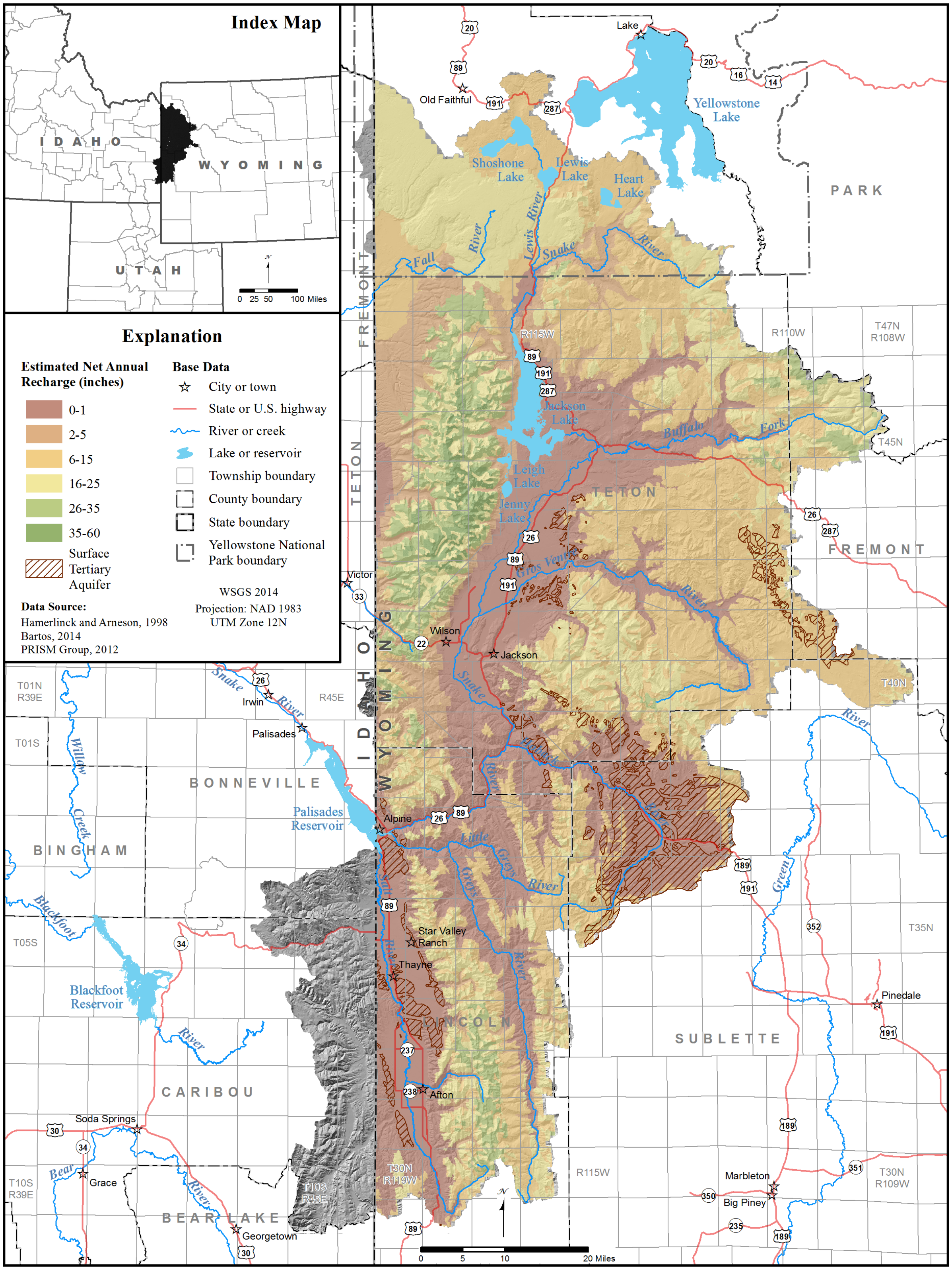

Figure 6-2. Estimated net annual aquifer recharge – surface Tertiary aquifer, Snake/Salt River Basin, Wyoming.

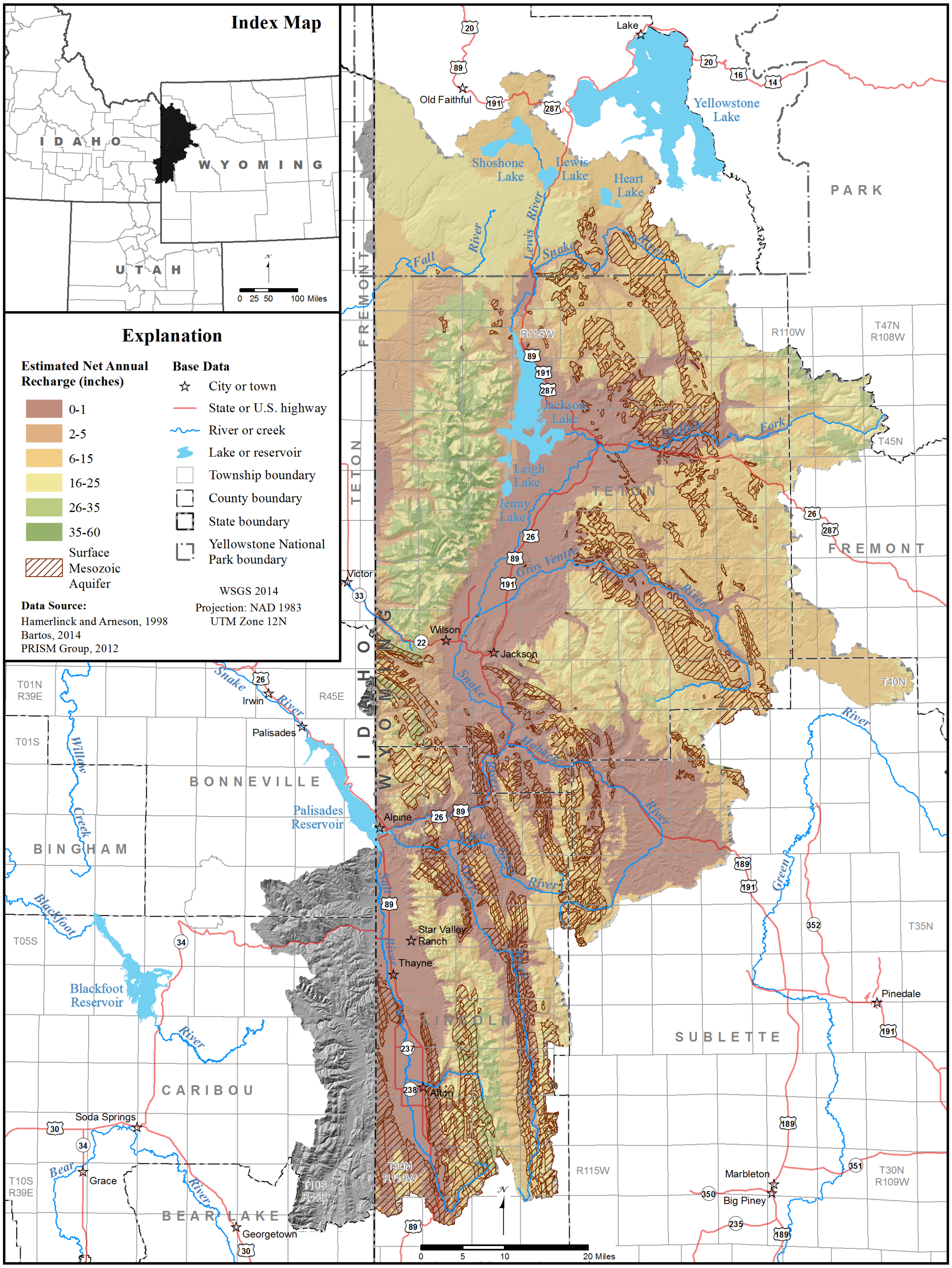

Figure 6-3. Estimated net annual aquifer recharge – surface Mesozoic aquifer, Snake/Salt River Basin, Wyoming.

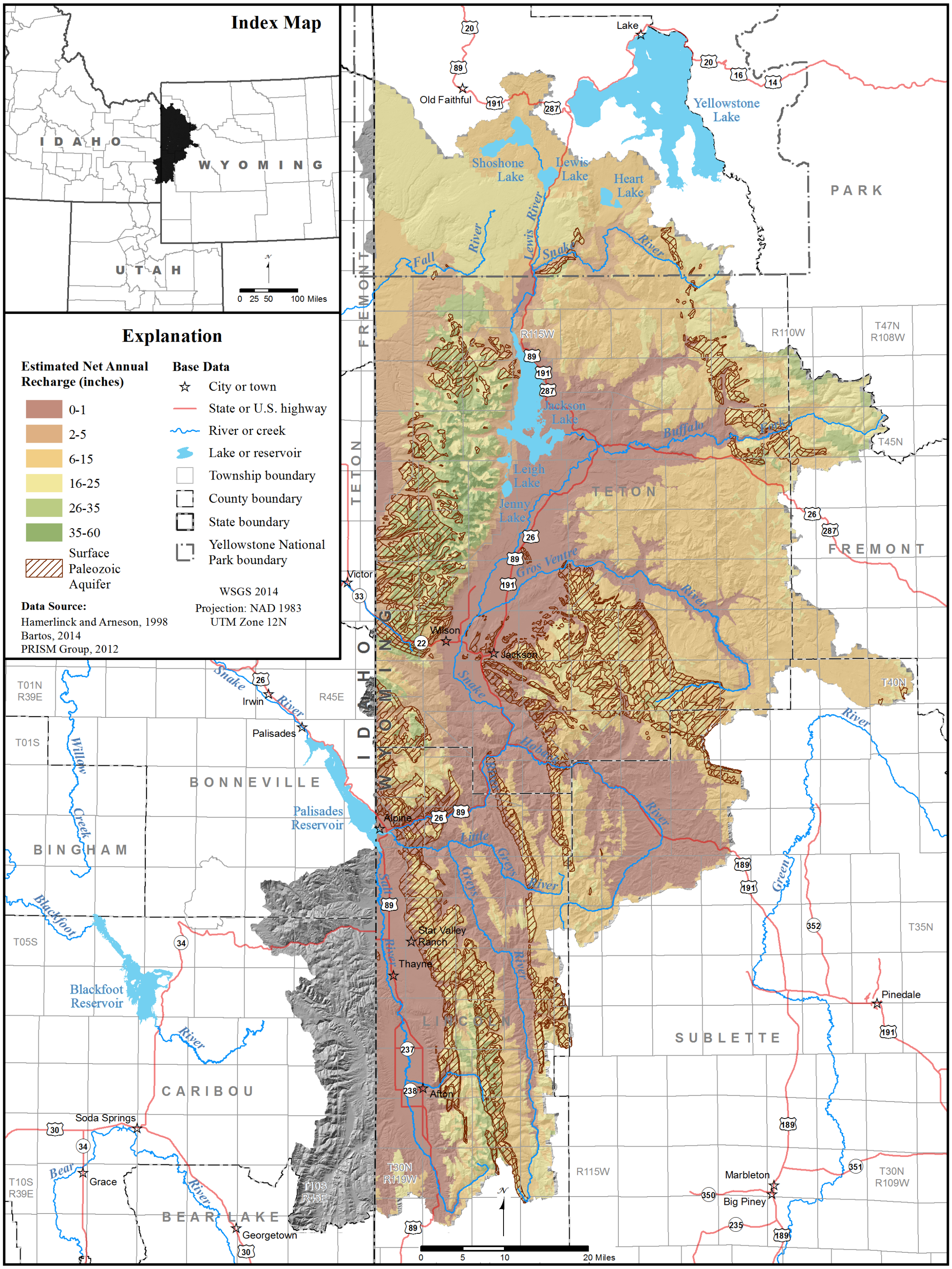

Figure 6-4. Estimated net annual aquifer recharge – surface Paleozoic aquifer, Snake/Salt River Basin, Wyoming.

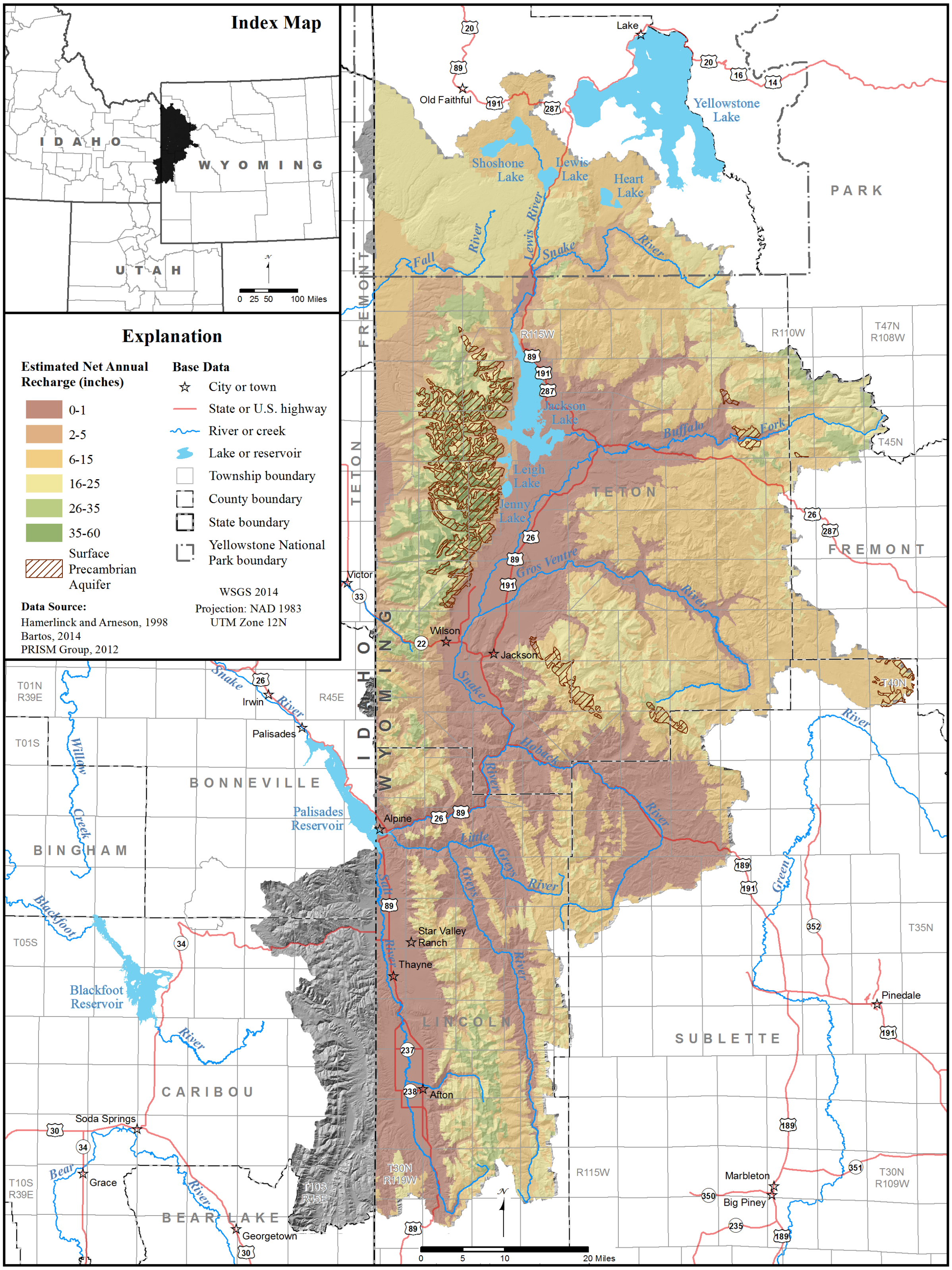

Figure 6-5. Estimated net annual aquifer recharge – surface Precambrian aquifer, Snake/Salt River Basin, Wyoming.

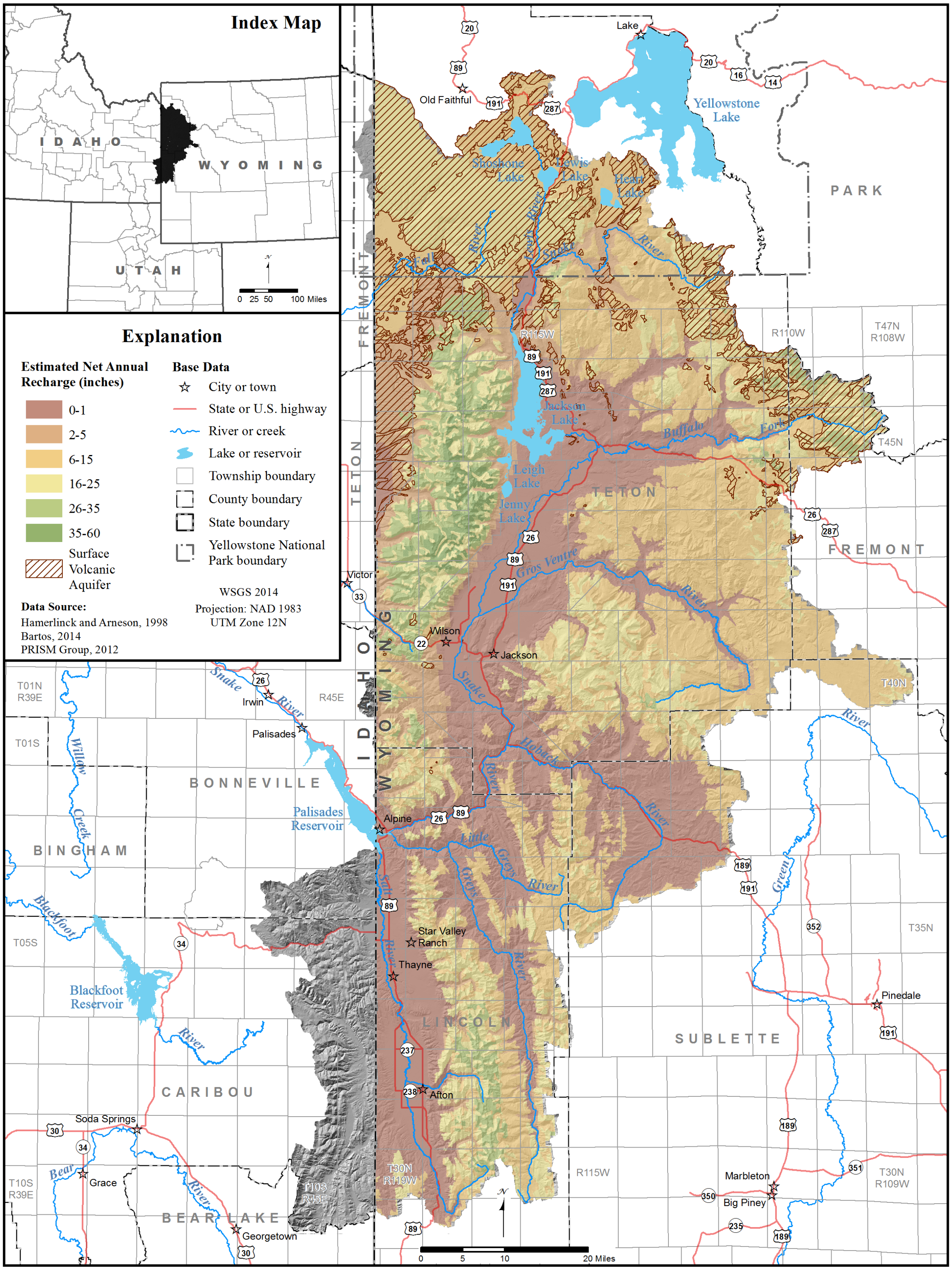

Figure 6-6. Estimated net annual aquifer recharge – surface Volcanic aquifer, Snake/Salt River Basin, Wyoming.

Basin ranges from less than one inch per year in the basin interior to over 35 inches per year in the surrounding mountains (Hamerlinck and Arneson, 1998). Mountains and foothills receive more recharge than basin lowlands due to environmental attributes characteristic of highland zones:

- Greater amounts of precipitation and more persistent snow pack (**fig. 3-3**),
- More abundant vegetation,
- Soil and vegetation combinations more favorable to infiltration,
- Lower rates of evapotranspiration,
- Better exposure of the upturned and weathered edges of hydrogeologic units facilitates infiltration because zones of higher permeability often parallel bedding, and
- The presence of structural features that enhance recharge (e.g., faults, fractures, joints, and fault/fracture-controlled surface drainages).

Figure 6-7 shows how recharge efficiency, defined as a percentage of average annual precipitation (R/P), varies throughout the Wyoming portion of the Snake/Salt River Basin and suggests what environmental factors exert control on recharge. Recharge is most efficient in the mountains of the Teton, Absaroka, Gros Ventre, Salt River, Snake River, and Wyoming ranges and are also slightly higher on the Yellowstone Plateau. The dataset for **figure 6-7** was generated by dividing 4,000-meter grid cells and assigning values for average annual, aquifer recharge (**fig. 5-1**) and average annual precipitation (**fig. 3-3**) to each cell; both data sets were obtained from the SDVC aquifer vulnerability study prepared for the State of Wyoming (Hamerlinck and Arneson, 1998).

Average annual recharge (**fig. 5-2**) is based on percolation percentages for different soil/vegetation combinations multiplied by average annual precipitation for the 30-year period from 1981 to 2010. Total average annual precipitation has been estimated (PRISM, 2013) as 9,852,837 acre-feet for the larger Snake/Salt River Basin shown in **figure 3-3** and 9,137,284 acre-feet for the Wyoming portion exclusively (**table 8-2a**). Although this approach does not fully consider all factors that affect recharge, initial infiltration and precipitation levels are probably the most important factors on a regional scale. Consideration of the other factors listed above and in **section 5.1.3.1** should confirm the general pattern of recharge efficiency displayed in **figure 6-7**. However, as discussed previously (**sections 5.1.3.1** and **5.4**), local recharge rates may be dominated by site-specific hydrogeologic conditions (e.g., solution-enhanced fracture permeability). Lastly, Hamerlinck and Arneson (1998) indicated that some areas in the basin interior receive zero amounts of recharge (**fig. 5-2**).

Table 6-1 shows the percentage of surface area by specified range of recharge efficiency, as R/P and as determined via GIS analysis, for each of the six, age-classified, aquifer recharge zones (**pl. 2*; figs. 6-1*** through **6-6***)*.

Table 6-1 shows that most Quaternary and Tertiary aquifers receive recharge at efficiencies of six percent or less of precipitation. In contrast, most Mesozoic, Paleozoic, Precambrian and volcanic aquifers receive recharge at efficiencies greater than six percent, likely due to the fact that these aquifers are fractured and are exposed in upland areas. The consistently low recharge efficiencies calculated for Tertiary and Quaternary aquifer zones may reflect the subdued relief and greater aridity (**fig. 3-3**) within the interior of the Snake/Salt River Basin.

Recharge volumes for the established aquifer recharge areas were calculated with the following, general equation:

Average annual recharge volume (acre-feet) = Aquifer recharge area (acres) × Average annual recharge (f eet)

The outcrop areas assigned to aquifer groups in the recharge calculations **(figs. 6-1** through **6-6)** were determined from the hydrogeologic map (**pl. 2**) developed for this study. Average annual rates of recharge throughout the Snake/Salt River Basin (mapped in 100-meter cells) adapted from the Wyoming Groundwater Vulnerability Assessment

Table 6-1. Percent of aquifer recharge zones recharging at varying efficiencies.

Recharge Efficiency as annual recharge / annual precipitation, (in percent)	0-1%	2%	5%	6%	30%	35%	36%	40%	60%
Quaternary	2.72%	0.00%	1.22%	55.86%	0.00%	28.05%	5.14%	1.41%	5.60%
Tertiary	23.11%	22.69%	1.93%	23.77%	0.00%	24.96%	-	-	3.55%
Mesozoic	0.43%	0.00%	0.00%	38.37%	28.43%	12.04%	0.20%	0.13%	20.40%
Paleozoic	0.00%	-	-	22.13%	0.00%	22.42%	0.04%	0.21%	55.21%
Precambrian	-	-	-	8.87%	-	29.06%	-	-	62.07%
Volcanic	-	-	-	15.28%	0.00%	6.52%	5.19%	49.10%	23.91%

Handbook (Hamerlinck and Arneson, 1998) are shown in **figure 5-2**. Recharge rates were grouped into the five ranges to make **figure 6-7** more readable and to mitigate the uncertainties associated with the recharge calculations. Recharge rates for the aquifer recharge zones, mapped as polygons, were converted from inches to feet, and the average annual recharge volumes (in acre-feet) were calculated using the equation above.

Recharge calculations contained in this report do not incorporate confining unit outcrop areas (**pl. 2**). As noted in **section 5.2**, undifferentiated geologic units were included in the established aquifer recharge areas of the same age. Recharge calculations that exclude confining-unit outcrop areas provide a more conservative estimate of available groundwater resources. Furthermore, leakage from adjacent confining layers was also disregarded in this evaluation.

Table 6-2 summarizes calculated recharge for the Snake/Salt River Basin over the ranges of average annual recharge mapped on **figure 5-2** and the aquifer recharge zones displayed in **figures 6-1** through **6-6**. A "best total" amount for each range of recharge over the outcrop area of each aquifer group is provided in **tables 6-2** and **6-3** based on the recharge area for each whole inch of recharge in the database compiled for this study. The "best total" is calculated directly from the detailed cell-by-cell recharge data and the corresponding surface area.

Table 6-3 summarizes calculated, average annual recharge statistics from the more detailed calculations provided in **table 6-2**. Additionally, **table 6-3** provides a "best total," average recharge depth, delivered over the entire surface area of each aquifer recharge zone. An analysis of average recharge depths shows that high elevation Precambrian aquifers receive 2.141 feet (25.7 inches) of recharge compared to about 6.5 and 3.1 inches, respectively, in Quaternary and Tertiary aquifers. The Mesozoic aquifers, which crop out in highland areas located primarily in northern and central parts of the basin (**pl. 2**), receive 0.77 feet (~9.2 inches) of recharge. Infiltration through Paleozoic and volcanic strata provides about 53% of the basin's recharge.

In the Wyoming part of the Snake/Salt River Basin, the best estimate of total recharge is 2,620,738 acre- feet, or 29 percent, of total precipitation.

6.3 Summary

- Recharge is ultimately controlled by precipitation. Total average annual precipitation for the Snake/Salt River Basin (**fig. 3-2**) has been estimated as 9,852,837 acre-feet and 9,137,284 acre-

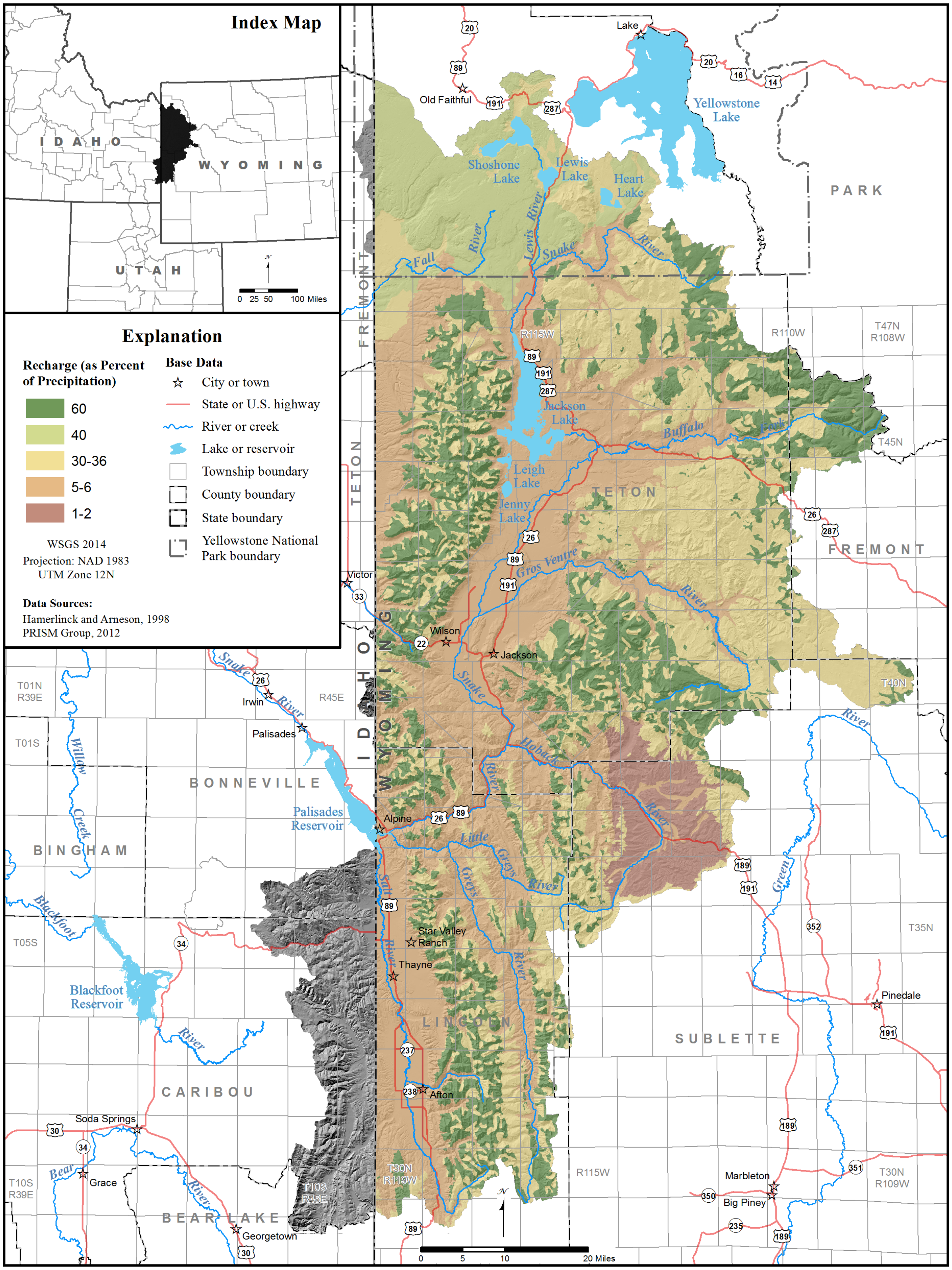

Figure 6-7. Aquifer recharge as percentage of precipitation using 1981 - 2010 precipitation normals, Snake/Salt River Basin, Wyoming.

Table 6-2. Snake/Salt River Basin average annual recharge calculations.

ERA	Range of Average Recharge per year: Inches	Range of Average Recharge per year: Feet	Outcrop Area Receiving Recharge: Acres	Average Annual Recharge: Best Total (Acre-feet)
Quaternary	0 1	0.00 0.08	354,454	27,212
	2 5	0.17 0.42	257,699	44,483
	6 15	0.50 1.25	312,577	301,593
	16 25	1.33 2.08	72,100	116,362
	26 35	2.17 2.92	15,819.76	39,827.59
	35 60	2.92 5.00	5,503.25	18,532.01
	TOTAL		**1,018,153**	**548,010**

ERA	Range of Average Recharge per year: Inches	Range of Average Recharge per year: Feet	Outcrop Area Receiving Recharge: Acres	Average Annual Recharge: Best Total (acre-feet)
Mesozoic	0 1	0.00 0.08	89,014	7,218
	2 5	0.17 0.42	126,424	21,664
	6 15	0.50 1.25	229,972	204,653
	16 25	1.33 2.08	76,859	130,242
	26 35	2.17 2.92	23,925	54,894
	35 60	2.92 5.00	0	0
	TOTAL		**546,194**	**418,671**

ERA	Range of Average Recharge per year: Inches	Range of Average Recharge per year: Feet	Outcrop Area Receiving Recharge: Acres	Average Annual Recharge: Best Total (acre-feet)
Precambrian	0 1	0.00 0.08	45	4
	2 5	0.17 0.42	9,015	1,849
	6 15	0.50 1.25	5,802	6,046
	16 25	1.33 2.08	35,977	61,237
	26 35	2.17 2.92	30,694	81,116
	35 60	2.92 5.00	19,617	66,317
	TOTAL		**101,149**	**216,569**

ERA	Range of Average Recharge per year: Inches	Range of Average Recharge per year: Feet	Outcrop Area Receiving Recharge: Acres	Average Annual Recharge: Best Total (acre-feet)
Tertiary	0 1	0.00 0.08	124,500	3,346
	2 5	0.17 0.42	8,904	1,484
	6 15	0.50 1.25	43,272	33,125
	16 25	1.33 2.08	5,613	8,499
	26 35	2.17 2.92	0.00	0.00
	36 60	3.00 5.00		
	TOTAL		**182,289**	**46,453**

ERA	Range of Average Recharge per year: Inches	Range of Average Recharge per year: Feet	Outcrop Area Receiving Recharge: Acres	Average Annual Recharge: Best Total (acre-feet)
Paleozoic	0 1	0.00 0.08	23,052	1,921
	2 5	0.17 0.42	87,918	15,417
	6 15	0.50 1.25	100,499	105,959
	16 25	1.33 2.08	204,497	348,515
	26 35	2.17 2.92	75,859.21	191,354.22
	35 60	2.92 5.00	9,513.47	30,040.68
	TOTAL		**501,339**	**693,207**
	Snake Salt River Basin TOTAL		***2,848,124***	***2,620,738***

ERA	Range of Average Recharge per year: Inches	Range of Average Recharge per year: Feet	Outcrop Area Receiving Recharge: Acres	Average Annual Recharge: Best Total (acre-feet)
Volcanic	0 1	0.00 0.08	31	3
	2 5	0.17 0.42	77,575	15,070
	6 15	0.50 1.25	116,972	131,911
	16 25	1.33 2.08	264,238	456,158
	26 35	2.17 2.92	40,185	94,687
	35 60	2.92 5.00	0	0
	TOTAL		**499,001**	**697,828**

[1] adapted from Hamerlinck and Arneson, 1998 and [2] PRISM, 2013

Table 6-3. Annual recharge statistics for Snake/Salt River Basin aquifer recharge zones.

Aquifer Recharge Zone	Recharge zone surface area (acres)	Percent of total basin surface area	"Best total" annual recharge volume (acre-feet)	"Best total" recharge as percent of basin total	"Best total" average recharge depth, in	
					feet	inches
Quaternary	1,018,153	35.75%	548,010	20.91%	0.538	6.5
Tertiary	182,289	6.40%	46,453	1.77%	0.255	3.1
Mesozoic	546,194	19.18%	418,671	15.98%	0.767	9.2
Paleozoic	501,339	17.60%	693,207	26.45%	1.383	16.6
Precambrian	101,149	3.55%	216,569	8.26%	2.141	25.7
Volcanic	499,001	17.52%	697,828	26.63%	1.398	16.8
Total, Volcanic through Quaternary zones	**2,848,124**	**100.00%**	**2,620,738**	**100.00%**	**0.920**	**11.0**
Total, Sedimentary Aquifers (Paleozoic through Quaternary zones)	**2,247,974**	**79%**	**1,706,341**	**65%**	**0.736**	**8.8**

[1] adapted from Hamerlinck and Arneson, 1998 and [2] PRISM, 2013

feet for the Wyoming portion of the basin (**table 8-2a**).

- Recharge controlled by precipitation and soil/vegetation combinations in the Wyoming portion of the Snake/Salt River Basin ranges from 0 to 54 inches (Hamerlinck and Arneson, 1998), with the lowest values occurring in the interior basins and the highest values in the upland drainages of the surrounding mountain ranges.

- Other factors controlling recharge may dominate locally (e.g., solution enhanced fractures); however, consideration of these factors should confirm the overall pattern of recharge and recharge efficiency.

- Recharge from precipitation to flat-lying Tertiary and Quaternary aquifers in the interior basin is generally less efficient than recharge to the exposed Paleozoic and volcanic aquifers in the mountainous areas. Recharge in the Snake/Salt River Basin is most efficient in higher elevation, Paleozoic terrains.

- Estimates of average annual recharge in the Snake/Salt River Basin are presented as a "best total" based on the cell-by-cell product of area and rate of recharge.